Chapter 14

Gas Hydrate in the Arctic and Northern North Atlantic Oceans

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1. INTRODUCTION

The northern North Atlantic and Arctic oceans are morphologically and geologically complex. The constructive axial plate margin of the northern North Atlantic is propagating through Fram Strait, forming a young oceanic crust in the Nansen Basin of the Eurasian end of the deep water Arctic Ocean (Fig. 1). A complex transform along the continental margin of the Laptev Sea is the present termination of this Atlantic-Arctic Ocean spreading center. The North American end of the Arctic Ocean is floored by older oceanic crust carrying a thick sediment prism in the western end of the Canada Basin. The Barents Sea, like the other wide shallow water margins of the Asian Arctic Ocean and narrower continental shelf elsewhere around the Arctic margin, is an epicontinental sea (Eldholm & Talwani, 1977).

The methane generating character of marine sediments is fundamental to the development of hydrate. Any area in which delivery of organic material is high and burial is rapid will lead to formation of biogenic methane. The Arctic and the North Atlantic Oceans are likely to be revealed as major hydrate provinces because the oceanographic conditions (around 0°C) are highly suitable for preservation and burial of organic material (>1.5%). Deeply buried sediments in the Arctic are rich in organic matter. The area comprises one of the largest contiguous sedimentary provinceswith significant amounts of organic carbon (Premuzic, 1980; Romankevich, 1984). The sedimentary framework has been similar in the North American end of the Arctic basin since mid-Mesozoic times and in the Eurasian end since not long after the formation of the plate margin in Magnetic Anomaly 23 times (~ 52 Ma bp) (Vogt, 1986; 1999; Eldholm et al., 1987).

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2. Biogenic gas is produced by the deep biosphere (Chapters 7 & 8).
3. Sedimentary successions throughout the region are regarded as having good gas generation potential.
4. 500 m is a minimum depth for finding hydrate-bearing areas.
5. Bottom water temperature at between the -1.5° C to +1.5° C. Three main areas where hydrate is likely to be found have been identified using these criteria (Fig. 5):

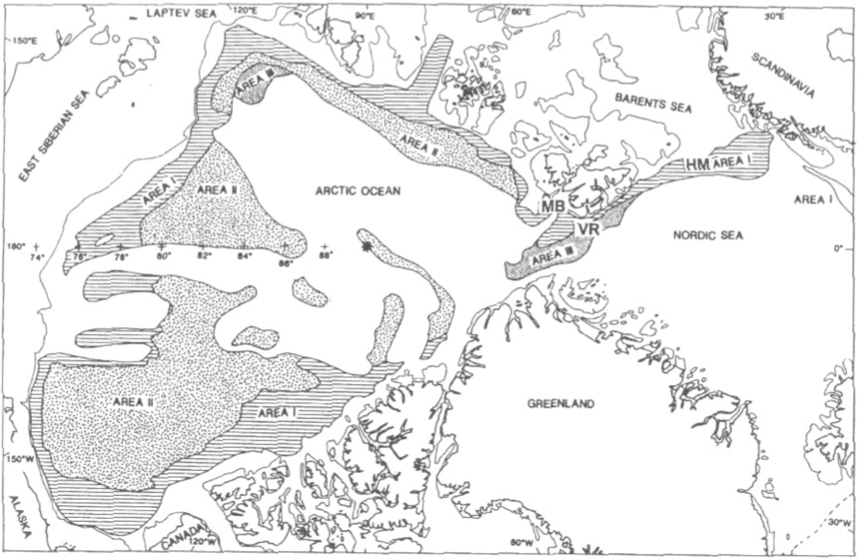

Figure 5. Hydrate likelihood areas, from Max and Lowrie (1993). Slope and abyssal areas separated in Arctic at about the 3,000 m contour. Sediment thickness data not included for areas to the south of dashed line passing across south Iceland. Area I. Continental slope areas between 500 m and 3,000 m follow recognized hydrate development in continental slope north of Alaska (Grantz et al., 1989). Area II. Abyssal areas and sedimentary basins not tied to continental shelf structure where sediment thickness exceeds 3 km. Area III. Areas of abnormally high heat flow associated with plate margin where gas could be sourced from thin sediments or where there is juvenile gas. Area III minimum sediment thickness of between 0.75 km -1 km in ridge vicinities (Knipovich and Laptev).

Area I. This area includes continental slopes between 500 m and 3,000 m water depth where sediment thickness is greater than 3 km. This region the water depth range in which hydrates have been identified along the North Slope of Alaska (Grantz et al., 1989). About 818,000 km^2 of the Arctic Basin and about 154,000 km^2 of the Northern North Atlantic are underlain by areas with these physical characteristics.

Area II. This area includes abyssal regions below 3,000 m (except in the continental slope-ward margin of the Wrangel Abyssal Plain where the 2,500 m contour has been mainly used) where sediment thickness is greater than 3 km. In abyssal areas, no identification of hydrate has yet been made, but if sufficient area is little explored due to difficult environmental conditions and its remoteness. Thick sediments in intracratonic basins on the East Greenland shelf (Jackson et al., 1991) may contain geological petroleum traps similar to those proven by drilling in the Troms-Hammerfest basins of

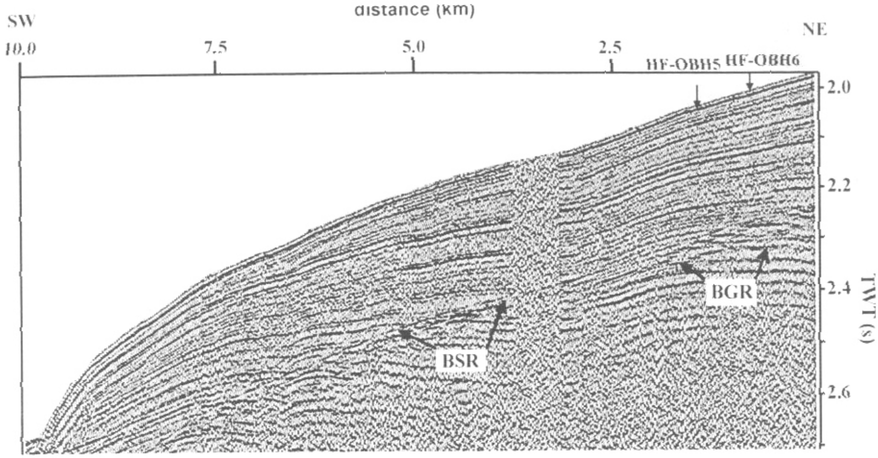

Figure 4. Section of seismic reflection profile based on a 2-liter airgun and a 6-channel streamer located at the Svalbard margin. The arrows mark the locations of the HF-OBH stations 5 and 6 at the sea floor. A strong BSR occurs at a depth of 0.25 s TWT bsf. The BSR parallels the sea floor, crosses the discordant sedimentary strata and is characterized by high amplitudes. Below the BSR the base of gas-bearing sediments is marked by the BGR (from Posewang and Mienert, 1999b).

3.4. Arctic Ocean

Although BSRs have not yet been identified in water depths below 2800 m on the north Alaskan rise (Grantz et al., 1976, 1989; Grantz and May, 1982; Grantz et al., 1989), it is likely that hydrate will be identified in deeper water. Lowrie and Max (1993) discuss a number of indirect identifications of phenomena, such as gas and fluid bursts, which have been used to infer the presence of hydrate in this little known province.

4. AERIAL EXTENT OF HYDRATE FORMATION

Hydrate, often with gas below, has been recognized in continental slopes and rises between about 500 and 3,500 m water depth (Eiken and Hinz, 1989, Mienert et al., in press). All Arctic and northern North Atlantic continental slope areas where sediment thicknesses are greater than about 3 km are potentially areas in which significant gas generation and consequent hydrate formation is possible. Prediction of gas production and the presence of hydrate, however, is uncertain.

A number of criteria are used in determining the area and thickness of potential hydrate development:

1. An average heat flow value of 30°/km for this region.

act as a low-pass filter on seismic signals. Above the BSR, frequencies up to 170 Hz predominate; below the BSR, frequencies of

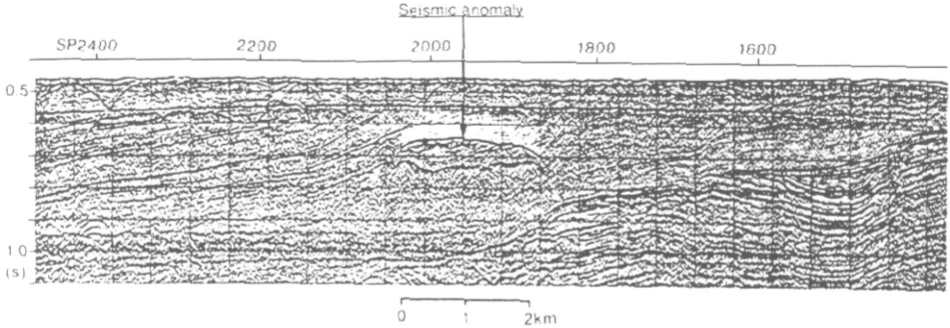

Figure 3. Section of a multi-channel reflection seismic profile located in the Barents Sea. In a depth of 0.17s TWT bsf a seismic anomaly appears interpreted as a BSR. The BSR crosses the dipping sedimentary strata, is characterized by high amplitudes and shows a limited lateral extension above a fault complex (from Andreassen *et al.* 1990).

less than 80 Hz prevail. Free gas, which is trapped below the BSR, might explain the high reflection amplitudes in this subbottom depth and the existence of a low-pass filter on seismic signals. The sealed free gas migrates into the overlaying strata, and therefore, the thickness of the free-gas layer below the BSR varies (Posewang and Mienert, 1999b). Due to the high-resolution character of the data, the so-called 'Base of the Gas Reflection' (BGR) (Camerlenghi and Lodolo, 1994) could be detected and the thickness variation could be calculated (Mienert et al., in press). The reflection amplitude of the BSR also varies according to the thickness of the free gas layer. Due to the short distance to the Vestnesa Ridge, which acts as a heat source (Vogt *et al.*, 1994), the sub sea floor temperature increases downslope. Therefore, the subbottom depth of the BSR decreases with increasing water depth from 0.26 s TWT bsf upslope to 0.22 s TWT bsf downslope (Posewang and Mienert, 1999b). Velocity analysis of multi-channel seismic data shows three distinct layers with different velocities (Andreassen and Hansen, 1995). A nearly 200 m thick layer between the sea floor and the BSR has an average velocity of 1630 m/s followed by a low-velocity layer of 100 m thickness (1450 m/s) and a zone of higher velocities. The high-velocity layer above the BSR is interpreted to contain gas-hydrated sediments, whereas the low-velocity layer indicates free gas beneath the BSR. The interpretation of a gas layer below the BSR was confirmed by velocity-depth models calculated from High-frequency Ocean Bottom Hydrophone (Hf-OBH) data (Posewang and Mienert, 1999b).

3.3. Greenland Margins

The North Greenland continental margin only locally appears to contain enough sediments to either generate sufficient methane or host a HSZ. However, this sediments corresponds with the occurrence of the BSR in seismic sections (Posewang and Mienert, 1999a).

A low-velocity zone within the HSZ reflects the complicated hydrate formation mechanism in this area (Posewang and Mienert, 1999a). At a depth of approx. 0.125 s TWT, the velocity drops from 1580 m/s to 1350 m/s, indicating free gas in the sediments. Above the free gas layer, a lithological boundary possibly acts as a seal for rising gas. The significant impedance contrast between the gas-bearing sediments above and gas-hydrated sediments below produces a strong reflection on seismic records in a depth of 0.125 s TWT bsf interpreted as the top of gas hydrates (Fig. 2).

3.2. Barents Sea Margin and Svalbard Margin

The largest contiguous sedimentary prism in the North Atlantic is along the western Barents Sea margin (Myhre and Eldholm, 1988), especially in the Bear Island Fan, where sediments are up to 7 km thick (Vorren et al., 1998; Hjelstuen, et al., 1999). Because rapidly deposited sediments derived primarily from a continental shelf area constitute good source beds, the west Svalbard sediment prism is likely to contain significant amounts of organic material. Moreover, the ocean continent boundary of the western Barents Sea is characterized by high heat flow (Eldholm et al., 1999) facilitating rapid generation of hydrocarbons. Hydrate has been identified in the Håkon Mosby Mud Volcano (HMMV) in the Bear Island Fan (Vogt et al., 1999; Ginsburg et al., 1999), in the Vestnesa Ridge (Vogt et al., 1994) and nearby (Posewang & Mienert, 1999) to the SW of the Yermak Plateau, and by inference within the Malene Bukta embayment (MB) in the Arctic margin immediately to the north of Svalbard (Cherkis et al., 1999) (Figs. 1) Both shallow gas and hydrate have been identified in sediments of the western Barents Sea slope (Eiken and Austegard, 1987; Eiken and Hinz, 1993). Seismic velocity profiles indicate trapped gas below hydrate on the upper continental slope (Austegard, 1982).

The Barents Sea gas hydrate site is at about 350 m water depth. A single shallow seismic reflector of anomalous high amplitudes cuts through dipping layers, interpreted as the base of a gas hydrate cemented layer (Fig. 3) (Andreassen *et al.*, 1990). The BSR that here has the appearance of a "bright spot" occurs in a depth of 0.17s TWT, corresponding to approximately 180 mbsf, one of the shallowest known BSRs observed in north Polar Regions. Velocity analysis from multi-channel seismic data show a high velocity layer above the BSR (>2400 m/s) interpreted as a gas hydrate layer (Andreassen *et al.*, 1990). The strong velocity decrease to values of about 1625 m/s below the BSR, is an indicator of free gas in the sediments.

The Svalbard gas hydrate site ranges in water depth from 860 m to 2350 m. A well-developed BSR exhibits strong amplitude variations, and parts of it show high amplitude reflections below (Fig. 4) (Posewang and Mienert, 1999b). Furthermore, frequency analysis revealed that sedimentary layers below the BSR are dominated by biogenic gas (Whiticar and Faber, 1989). This situation suggests that not all hydrocarbons derived from more deeply buried sediments have yet reached the HSZ

North of the northern sidewall of the Storegga Slide, the lower boundary of the HSZ is determined in high-resolution reflection seismic data by a strong BSR which occurs at a depth of approximately 0.35 s two-way travel time (TWT) (Fig. 2). According to the velocity analysis, the corrected depth range of the BSR is 250-285 mbsf (Posewang, 1997, Mienert and Bryn, 1997). The BSR is easily traceable throughout a grid of seismic profiles, indicating the large extent of gas hydrates in this area. The BSR cuts reflections from the dominant strata, mimics the shape of the sea floor and is characterized by high amplitudes. The blanking above the BSR possibly indicates an increase of the hydrate concentration in the sediments. Parts of the BSR along this section are disturbed and exhibit amplitude variations (marked with a,b in Fig. 2). Anomalous high amplitudes of crossed horizons and vertical wipe-out zones are typical indicators for the existence of free gas below the BSR.

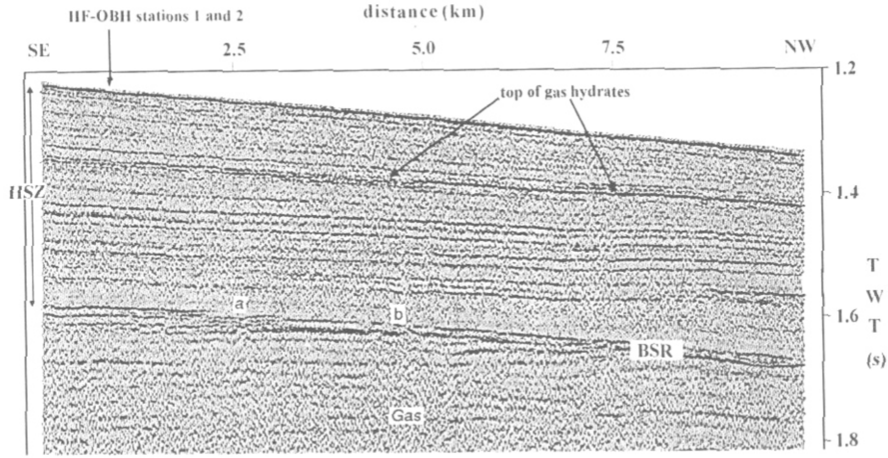

Figure 2. Section of seismic reflection profile acquired with a 2-liter airgun and a 6-channel streamer north of the northern Storegga escarpment. A strong BSR occurs at a depth of 0.35 s TWT bsf. Along this section, parts of the BSR are disturbed and exhibit amplitude variations (marked with a, b). The appearance of a second strong horizon in a depth of 0.125 s TWT is interpreted as the top of gas hydrates (from Posewang and Mienert, 1999a).

The velocity information from the HF-OBH data shows zones of alternating high and low velocity (Posewang and Mienert, 1999a). High velocities with a maximum of 1850 m/s indicate the existence of gas hydrates in a 180 m thick layer. Below these gas hydrate cemented sediments the velocity drops down to a minimum of 1400 m/s, a value lower than the SVS caused by gas-bearing sediments. The thickness of the low-velocity layer is not clearly identified. The transition between gas hydrate cemented and gas-bearing

Alpha-Mendeleyev Ridge are from 4 km to 6 km thick, but occur mainly within the continental shelf. Sediment thicknesses elsewhere along the Eurasian continental margin appear to be no more than 2 km to 4 km thick.

The Nansen and Amundsen basins are underlain by the youngest oceanic crust zone that represents the propagation of the North Atlantic ridge. These are conjugate basins which are formed from a single axial spreading ridge. Sediments in both basins formed a single prism over extensional crust until establishment of the ridge, at which time the sediments in the Amundsen Basin became more oceanic in character, except at the North American and Eurasian ends where continental sedimentation remains an important influence (Thiede, et al. 1990).

In general terms, the Gulf of Mexico may serve as a well explored analogue for the lesser-known Canada Basin. Both developed at about the same time in the same manner and are characterized by a fixed, major sediment source. Sediment samples from the central Canada Basin have been mainly taken from the shallower water areas of the Alpha-Mendelyev Ridge complex and the Northwind Ridge (Darby et al., 1989) where sedimentary successions in many grabens containing basal Cretaceous beds no more than 1.4 km thick. A few depocenters of sediment thickness > 4 km and >6 km occur in the Chukchi Trough and in the Alpha ridge and along its margins.

3. OCCURRENCE OF BSRs AND HYDRATE LOCALITIES

3.1. Norwegian Margin

Two provinces on the mid-Norwegian Margin show BSR. Whereas the reflectors on the outer Vøring Plateau are related to diagenesis (Skogseid and Eldholm, 1989), the BSR in the vicinity of the Storegga slide are related to gas hydrates (Bugge, 1983; Mienert and Bryn, 1997, Mienert, et al., 1998, Bouriak et al., 2000). These BSRs are located at the seaward termination of a thick wedge of Plio-/Pleistocene sediments, and it is likely that fast sedimentation caused burial of large amounts of organic material. It has been suggested that gas hydrates have destabilized the slope in this area, and that this is one reason for catastrophic slope failure (Bugge et al., 1987, Mienert et al., 1998). Generation of this slide has been related to tsunamis on the facing Norwegian coast (Dawson et al., 1988, Bondevik et al., 1997).

The Storegga Slide is one of the world's largest submarine landslides having moved a total of 5600 km^3 of sediment with an original thickness of the slumped layer of up to 450 m from an area with a size comparable to that of mainland Scotland (Jansen *et al*., 1987; Bugge *et al*., 1988, Evans et al., 1996). A coincidence of dissociation of gas hydrates and slope failures exists at the Mid-Norwegian continental margin (Bugge *et al.,* 1987; Jansen *et al*., 1987; Mienert *et al*., 1998). High-resolution seismic data allowed to identify two parallel-occuring BSR and associated velocity anomalies in this area (Posewang & Mienert, 1999a) indicating a complex gas and gas hydrate system. Low levels of methane and minor propane from three ODP drill sites on the Vøring Plateau sequence of sedimentary strata from the Late Paleozoic to the Quaternary (Faleide et al., 1993; Gudlaugsson et al., 1997). However, Neogene uplift and Pliocene-Pleistocene glaciations caused severe erosion of the inner parts of the Barents Sea. Two depocenters developed in the adjacent Norwegian-Greenland: the Bjørnøya Fan south of Bjørnøya and the Storfjorden Fan north of it. More than half of the sediments in these fans was deposited during the last 3 Ma (Eidvin et al., 1993; Sættem et al., 1994; Faleide et al., 1996, Elverhoi et al., 1998).

2.2. Arctic Ocean

The Arctic Ocean floor comprises two distinct major tectonic units. The Amerasian Basin to the Alaskan/Asiatic side of the Lomonosov Ridge (Fig. 1) has a complex internal geological history related to terrane accretion that can be traced into the Pacific Ocean prior to closure of the Bering Sea. The Canada Basin was formed earlier than the Eurasian Basin that lies between the Lomonosov Ridge and the Barents Sea, through which an active constructive plate margin currently passes. The floor of the Arctic Ocean consists of a series of roughly parallel ridges and basins extending from the North American continent to the Eurasian continent. Upper Paleozoic through Cretaceous sediments, including thick shale sequences, have been proven from northern Alaska to northeastern Ellesmere Island, and presumably occur in slope prisms (references in Max and Lowrie, 1993).

The Alaskan/Asiatic end of the Arctic Ocean (Fig. 1) contains the largest single basinal area, the Canada Basin, which is about 1,100 km X 600 km. It is underlain by earliest Jurassic, mid-Jurassic, or mid Cretaceous oceanic crust, and is the oldest part of the Arctic Ocean floor. The abyssal plains, which are underlain by at least 4 to 6 km of sediment, and up to over 10 km of sediment locally, lie at depths of 3 km to 3.9 km. The Makarov Basin lies between the continental fragment of the Lomonosov Ridge and the Alpha-Mendeleyev Ridge. Sediments in the deeper oceanic parts of this basin vary from 1 to 6 km, with greater thicknesses along the Alaska-facing flank of the Alpha-Mendeleyev Ridge.

Up to 4 km of Quaternary sediments occur in the outer sedimentary prism of the Alaskan North Slope overlying up to between 10 km and 12 km of Tertiary through Upper Paleozoic sediments. Smaller sedimentary basins north of Greenland at the juncture with the Alpha Ridge contain sediments between 8 km and 10 km thick. Nearby small sedimentary basins contain sediment between 2 km and 4 km thick. Sediments from 4 km to 8 km occur in the western North Alaska slope, with a major depocenter containing sediment up to 10 km to 12 km thick near the junction with the Northwind Ridge. The continental slope along the East Siberian Sea contains a narrow depocenter from 8 km to 10 km thick that is part of a larger sediment prism extending into the Wrangel Abyssal Plain. The thickest sediments along the junction with the Mendeleyev-Northwind-Chukchi Cap region at the Asian termination of the

2. Tectonostraticgraphic framework of the Arctic and northern North Atlantic Oceans

2.1. Northern North Atlantic

The Norwegian - Greenland Sea extends from Iceland to the Fram Straits (Fig. 1) and can be divided into a number of tectono-sedimentary provinces controlled by the transform-ridge system. Sediments immediately north of Iceland are up to 1 km thick but thin rapidly to less than 200 m thick in ponded areas along the remainder of the Kolbensey Ridge to the Jan Mayen Fracture Zone. Quaternary sediments on the southeast Greenland margin are up to 2.5 km thick and overlie at least 4 km thick Tertiary and Mesozoic sediments. Sediments on the Jan Mayen Ridge are up to 3 km thick. Sediment thickness variation in the Lofoten and Greenland Basins is characteristic of passive continental margins; thickest sediments along the continental slope and gradually thinning toward the ridge

The Norwegian margin developed during continental rifting between Laurentia and Eurasia, which culminated in Late-Paleocene/Early Eocene break-up (Skogseid et al., in press). Due to the Iceland hotspot mantle temperatures were increased during rifting and break-up, leading to extensive volcanism (Eldholm et al., 1989). The mid-Norwegian margin consists of three rifted margin segments (from south to north): the Møre Margin, the Vøring Margin, and the Lofoten-Vesterålen Margin, and an approximately 200 km long sheared margin segment which constitutes the southern boundary of the Vøring Margin (Figure 1). Extension of the entire area stopped after continental break-up, and apart from minor Tertiary doming the area became tectonically quiet. Doming focussed along the shelf break, and is manifest as the Helland Hansen Arch, and the Naglfar, Vema and Ormen Lange domes. The proposed mechanisms for these domes include ridge-push and differential compaction and asymmetric sedimentation (Doré et al., 1997; Vågnes, 1997). Whereas Eocene to Miocene sedimentation along the margin was moderate, Pliocene and Quaternary glaciations increased sediment input, and led to an up to 2 km thick wedge of clastic sediments east of the dome structures. After the last glacial maximum sedimentation on the mid-Norwegian margin was dominated by submarine mass-wasting (Vorren et al., 1998) potentially triggered by earthquakes and gashydrate dissociation due to climate change (Bugge et al., 1988; Mienert et al., in press).

The Barents Sea is an epicontinental sea extending between Norway and the Svalbard archipelago. It is bounded by Cenozoic passive margins in the north and west. The margin north of Svalbard is a volcanic rifted margin with related igneous intrusions reaching far south into the Barents Sea. The western margin of the Barents Sea is a sheared margin (Eldholm, 1987; Faleide et al., 1991, 1993). Wrench tectonics and an opening component to the predominantly shear setting resulted in complex deformation of the southwestern Barents Sea (Rønnevik & Jacobsen, 1984; Riis et al, 1986, Gabrielsen & Færseth, 1988). The sedimentary strata above the Paleozoic basement comprise an almost complete bacteria feeding hydrate formation (Chapter 8). Thus, the hydrocarbon-generating potential of marine sediments along this continental margin can be expected to have provided an excellent host for methane generation.

Hydrocarbon exploration in the Arctic has yet to move into many areas where hydrocarbons are likely to be concentrated. However, it is a great challenge because of the economic constraints associated with extreme cold in a remote area, shifting sea ice, environmental concerns, and very difficult logistics. Potentially methane-rich sediments almost certainly underlie large areas. It can be inferred that gas and oil, as well as hydrate deposits, will be more widely found than is currently proven.

Heat flow, which is critical to the thickness of the hydrate stability zone (HSZ) varies considerably in the Arctic and northern North Atlantic Oceans. Sea floor in the age range 100-200 my is 45-55 mW/m^2, younger sea floor has higher heat flows and thinner sediment cover (references to heat flow in Max and Lowrie, 1993). On active ridge sites to 3-4 Ma off-ridge heat flows average about 300 mW/m^2 with some heat flow measurements nearly 400 mW/m^2. The oceanic crust of the northern Greenland-Norwegian Sea has a high heat flow of between 100 and 200 mW/m^2 (Vogt and Sundvor, 1996).

The presence of natural submarine gas hydrates is commonly inferred from seismic reflection data (e.g. Hyndman and Spence, 1992). The base of the stability zone for gas hydrates (HSZ) is geophysically identified by the occurrence of a bottom simulating reflector (BSR) (Stoll et al., 1971). The BSR is a reflection at the boundary between a normal velocity layer or high-velocity gas hydrate cemented sediments and the underlying low-velocity gas-bearing sediments. Whereas compressional velocity values of 1700-2400 m/s are known to be typical for gas-hydrated sediments (Andreassen et al., 1990; Katzman et al., 1994; Lee et al., 1994; Minshull et al., 1994; Andreassen et al., 1995) values below the sound velocity of sea water (SVS) indicate free gas in the pore space. The BSR mimics the shape of the sea floor, often cuts the dominant stratigraphy and is characterized by a high, reversed polarity event (e.g. Lodolo *et al*., 1993; Katzman *et al*., 1994; Andreassen *et al*., 1995).

Oceanic hydrate (Chapter 6) has been geophysically recognized in deep water in a continuous zone along the North Slope of Alaska, in isolated localities in the Barents Sea (Laberg and Andreassen, 1996) and Norwegian continental margins (Mienert et al., 1998, Mienert and Posewang, 1999), and at least one locality in the eastern Labrador Sea (Fig. 1). In addition, hydrate formed independently from the presence of subsea permafrost (Chapter 5) and has been recognized in the Barents Sea (Løvø et al., 1990). Although considerable seismic data exist for the Barents Sea and Norwegian continental margin (Vorren et al., 1993), difficulty in carrying out seismic, bathymetric, and oceanographic surveys have yielded little data for the ice-covered Arctic basin as a whole.

Figure 1. Location and geographical names of generalized major basins, ridges and geological features in the Arctic and northern North Atlantic Oceans. From Max and Lowrie (1993). Polar equal area projection. Dot on Lomonosov Ridge is North rotational Pole. AR, Aegir Ridge; BAP, Barents Abyssal Plain; BB, Boreas Basin; BI, Bennet Island; CC, Chukchi Cap; EI, Ellesmere Island; FAP, Fletcher Abyssal Plain; FJI, Franz Joseph Islands; FS, Fram Strait; HM, Håkon Mosby Mud Volcano; GB, Greenland Basin; GFZ, Greenland Fault Zone; GS, Greenland Sea; I, Iceland; JMF, Jan Mayen Fault Zone; KBR, Kolbensey Ridge; KNR, Knipovich Ridge; LB, Lofoten Basin; LS, Labrador Sea; MB, Malene Bukta; NB, Northwind Basin; NOB, Norway Basin; NR, Northwind Ridge; NS, Nares Strait; NOS, Norwegian Sea; NSL, North Slope; PB, Prudhoe Bay; PAP, Pole Abyssal Plain; SAP, Siberian Abyssal Plain; SS, Storegga Slide; SV, Svalbard; V, Vestnesa Ridge; VP, Vøring Plateau; WAP, Wrangel Abyssal Plain; YFZ, Yermak Fault Zone; YP, Yermak plateau.

The Norwegian margin, including the northern North Sea and the Barents Sea (Vorren et al., 1993) along with the North American end of the Arctic Ocean and adjacent land areas (Chapter 5), are proven hydrocarbon provinces. Because the more deeply buried sediments have provided organic material that transformed into gas and oil, sediments in the upper 2 to 3 km of sediment which have not entered the oil window of hydrocarbon maturation (Max and Lowrie, 1993) are likely to provide a rich feedstock for methanogenic methane has been generated, there is a thick HSZ in which hydrate could form. About 1,403,000 km^2 of such area occurs in the Arctic.

Area III. Two relatively small areas of thin sediment overlie active transform/ridge systems in which it is known that gas and hot hydrothermal fluids are generated as a by-product of magmatic and volcanic activity. It is possible that hydrothermal fluids would deliver methane to sediments that would otherwise be too thin to generate its own gas. This area consists of about 35,000 km^2 of the Arctic Basin and about 80,000 km^2 of the northern North Atlantic.

The HSZ increases in thickness with increasing depth (Chapter 6) (Miles, 1995). 450 m represents a reasonable average thickness for the HSZ in Area I. For Areas II and III, in deep and very deep water, a thickness of about 700 m is used as a reasonable average thickness.

The thickness of the HSZ may be less important than a mechanism that allows hydrate to concentrate. The HSZ off SE Japan, for instance, is relatively thin (Chapter 18), but the hydrate there is highly concentrated.

Estimations of hydrate and gas were made by Max and Lowrie (1993), but are now regarded as being high (Kvenvolden, 1998).

Conclusions

Gas hydrate has been identified in the North Atlantic and Arctic Oceans. Its extent is not known in detail owing to lack of field data. Geophysical identifications of hydrate along the Norwegian continental margin have been proved by drilling (also see Chapter 23) and seafloor sampling (Vogt et al., 1999).

If the methane generating character of the sediments in the Canada Basin is appreciable, then enormous volumes of hydrate could be present.

Under-ice survey from submarine should resolve the Hydrate Economic Zone (Glossary of Terms) and allow quantification of hydrate.

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